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**"ALEXANDRU IOAN CUZA" UNIVERSITY OF IASSY**
**FACULTY OF PHYSICS**


# Contributions to micromagnetic modeling of switching in ferromagnetic mediums

**- Summary of the Doctoral Dissertation-**


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***IASSY, September 2013***

**Acknowledgement**

The present scientific work represents the outcome of the fructuous guidance and co-operation that I enjoyed from the part of PhD Professor Alexandru STANCU, whom I wish to thank. I want to express my gratitude to Prof. Stancu for his pedagogy lesson from which I have learned how to perform the research, as well as for our scientific discussions that played a very important role in building my scientific house.

I also thank to the members of the CARPATH Center of Excellence, who guided me all along the period of my preparation for presenting my doctoral dissertation, and especially for the constructive critics and for the ideas they offered to me. I also express my thanks to PhD Lecturer Laurentiu STOLERIU for the scientific aid lent in elaboration and understanding of the parallel calculus algorithms.

At the same time, I want to express my gratitude to the team from the Department of Digital Communications from the "Al. I. Cuza" University of Iassy, for their support, patience and co-operation during the entire period of thorough study.

Last, but not the least, I want to express my thanks to my wife, Simona, for her complete confidence, for continuous moral and spiritual support, and for offering me an adequate ambiance for my human development.

I thank my parents for their financial and moral support, for bringing me up and educating me. You are a worth following model for me and I will be grateful to you all my life.

*This work was supported from the Social European Fund from Romania, under the leadership of the Management Authority for the Operational Sectorial Programme for the Development of Human Resources 2007-2013 [Grant POSDRU/CPP 107/DMI I.5/S/78342].*

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This doctoral dissertation was accomplished during the last three years (1 October 2010- 30 September 2013). The dissertation was prepared within the Laboratory of Modeling and Simulation, Faculty of Physics from the “Al. I. Cuza” University of Iassy, and the Department of Digital Communications of the “Al. I. Cuza” University of Iassy.

The dissertation “Contributions to micromagnetic modeling of switching in ferromagnetic mediums” is structured in *three chapters* preceded by an *Introduction* and ended with *General conclusions* and *Dissemination of the scientific activity*.

*Chapter I* has a documentary character, presenting the notion of critical curve for a single domain particle and the working hypotheses within the Stoner-Wohlfarth model. The next chapter refers to the switching process for a SAF structure whose ferromagnetic layers are represented by means of two macrospins. The structure of synthetic antiferromagnet SAF is presented as being the active part of the MRAM memory, built from two ferromagnetic layers coupled with the third layer, which determines an antiferromagnetic coupling structure. *Chapter 3* presents the results obtained in the determination of the working region for a SAF structure, by means of some micromagnetic models and the switching processes occurred in amorphous nanowires.

The scientific documentation of the dissertations is materialized in the 128 bibliographic references, representing relevant titles from the specialized literature.

The *objectives* of the dissertations consist in the presentation of the switching processes in SAF-type structures and amorphous nanowires. The SAF structures were characterized by determining the switching diagrams, the interior and the exterior critical curves. Studies concerning the influence of SAF structure size on the working regions and the switching diagrams were performed. Other studies were also carried out, presenting the influence of the time of field sequence application on the switching process, also showing off a method to reveal the switching process by means of the variation of the magnetic moments projections in the direction of easy magnetization axis during the simulation. Finally, we present the methods for result validation by fitting the external critical curves obtained both in the macrospin models and in the micromagnetic models, by means of the analytically determined saturation curves.

The dissertation starts with the bibliographic chapter “*Stoner-Wohlfarth model*” (SW) which represents the simplest theoretical model for the description of processes of small ferromagnetic particles magnetization, used in digital magnetic storage (diskettes, hard-disks and magnetic tapes), due to the magnetic moments polarization through coherent rotations under the action of an external magnetic field. The notion of critical curve of a single-domain particle with axial anisotropy is introduced through the association of an astroid that can be used to find the equilibrium state of the magnetic moments when applying a field, by using a geometric construction.

The chapter "*Stoner-Wohlfarth model for a system of two antiferromagnetically coupled ferromagnetic layers*" presents a simplified model for the treatment of an active memory zone, called "memory cell", where, for simplification, the two ferromagnetic layers are represented by two antiferromagnetically coupled S-W particles. This chapter is structured in four sub-chapters that treat this structure from energetic and dynamic standpoints.

"*The determination of the SAF structure working region"* set the theoretical bases on the sequence of applied magnetic field in order to induce the switching of the SAF structure macrospins without altering the neighboring memory cells.

The next sub-chapter treats from an energetic standpoint the switching process from the SAF structure, analytically determining the minimums and maxima of the external magnetic field applied along the easy magnetization axis and perpendicular to it respectively, which results in a controlled commutation.

The sub-chapter *"Numerical model for the study of two antiferromagnetically coupled S-W particles"* is dealing, like the previous one, with macrospin switching from an energetic point of view, but it presents the numerically determined results concerning the regions of the contour curves and the influence of these regions with antiferromagnetic coupling, magnetocrystalline anisotropy, magnetization of the ferromagnetic layers and their thickness.

In the last sub-chapter, entitles "*Dynamic model for the study of two antiferromagnetically coupled S-W particles",* the working regions are determined for a memory cell, knowing in details the trajectories of the two magnetizations when applying an external magnetic field, having an already known shape. By means of this model, we determined the switching diagrams for the SAF cylindrical structures with elliptical basis, consisting of two *Permalloy* ferromagnetic layers with the height of 5 nm and 7 nm respectively. In order to simulate the role played by the antiferromagnetic coupling of the third layer, which is used in the real devices, we introduced a new term of exchange energy, whose value is different from zero only at the interface between the two ferromagnetic layers, having a negative sign as compared to the term for ferromagnetic exchange energy. All along the simulation, we considered a constant for the exchange antiferromagnetic coupling $A_{anti}$, whose value was established at $A_{anti} = -5\cdot10^{-14}$ J/m [1].

The basis of the first sample was an ellipsis with the major axis of 24 nm (in the Ox direction) and the minor axis of 20 nm (in the Oy direction). The elliptic bases of the two samples used for simulation were the double and trice of the first sample basis. We maintained the same value for the thicknesses of the ferromagnetic layers along the Oz direction, namely 5 nm and 7 nm. Within the simulation, we considered the entire volume of the ferromagnetic layer as being concentrated in one point (the point of application of the magnetic magnetization vector).

In order to determine the switching diagrams of the SAF structures whose properties were presented, the field component H_puls was varied between 0 and 160 mT, with an 1 mT step, and the field component H_bias was varied between 0 and 160 mT, with the same variation step [1].

We simulated the switching diagrams within the SAF model for two macrospins whose contact surfaces are double from one sample to another, in order to reveal the size effect on the switching [1]. From the result figures, one can see the evolution of the internal and external critical curves with the modification of the sample size. One can notice that the extremities of the internal critical curves have smaller values in the plane of field component application when the sample dimensions are increasing. The switching diagrams of the critical curves give the possibility to conclude that both, the internal and the external critical curves preserve the same shape, but the critical curves in this model are not independent on the sample size; they are influenced significantly by the demagnetizing field in the direction of the major ellipsis axis. In this respect, we have differences between the results obtained through the SAF model for two macrospins, and the results obtained in the micromagnetic model, for the study of SAF memory switching.

In order to verify the results, we fitted the dynamically determined external critical saturation curve, with the analytically determined saturation curve. From the fitting graphic of the external curves to the saturation curves, one can notice that there are systematic deviations between the two curves. One can conclude that the best fitting can be obtained for the critical curve whose dimensions are larger. The difference ranges somewhere between 2 and 3%. The difference between the "theoretical" critical curve (saturation curve) and the external critical curve for the two antiferromagnetically coupled macrospins, determined with the LLG equation can be explained through the relatively big value of the damping constant used by us for simulation ($\alpha$). A smaller value of the damping constant drastically influences the simulation duration for the simulations from the micromagnetic model which is to be presented.

*Chapter 3*, entitled "*Micromagnetic model for the study of a SAF memory switching"* is structured in 7 sub-chapters and treats the switching process of some magnetic samples digitized through finite elements. The sub-chapter "*Numerical calculus methods"* presents the advantages and the manner of implementation of the calculus methods in micromagnetism: the method of finite differences and the method of finite elements.

The next subchapter presents the calculus system used in micromagnetic simulations that made possible to reduce the calculus time from 300,000 h for a switching diagram on a processor, to about 1000 h.

The sub-chapter 3 presents the software group used in micromagnetic simulations. In order to check up the accuracy of the results obtained from simulations with Magpar (Parallel Finite Elements Micromagnetic Package) [2], we implemented the test problems offered by [3]. The standard form of the Magpar program did not integrated the antiferromagnetic exchange interaction necessary to simulate the SAF structures. In this connection, we introduced this type of interactions in this program package [1].

A problem of interest was the determination of the calculus performances of the Magpar program package [2]. This study was accomplished within our cluster [4], in order to estimate the best distribution of a problem on a number of digital computers. In order to determine the performances of this program, we proposed to make a micromagnetic study of a thin *Permalloy* film, whose thickness varies from 20 to 1000nm with a 20 nm step, within which to determine the magnetic domains configuration. After having compared the time of execution and the necessary memory utilized by each processor, our conclusion was that the minimum time of execution can be obtained for our hardware, at about 100 MB RAM per processor.

Within subchapter "*Micromagnetic analysis of the commutation and the domain structure of metallic amorphous wires"* we presented a micromagnetic study on the generation of magnetic structure both in amorphous wires and in glass-coated amorphous wires, where the accent was set on the effects of composition, stress and magnitude. The samples were cylinders of various diameters and lengths, digitized through a tetrahedrons grid, and the solution of the LLG equation was computed in each knot of the grid. We chose cylinders with the diameter of 4 μm and length from 10 μm to 150 μm for our study.

A critical point in the micro simulations based on the finite element method is the exchange length characteristic for the samples, which must exceed the maximum distance between two neighboring nods Taking into account other reported estimates related to the exchange length [5], as well as those related to the domain walls thickness for amorphous wires [6], we chose a finite digitization parameter (maximum distance between two neighboring nods) of 200 nm, which results in problems with dimensions ranging between 130,000 and 2,000,000 elements [7].

In order to study the effect of the sign of the magnetostriction coefficient on the domain structure and the magnetization processes in amorphous wires, we took into account two types of materials characterized by two typical parameters.

The sub-chapter 5 presents a study that determines the influence of the construction of digitization grid on the magnetic moments orientation from the SAF structure. We used two methods for digitization of the structure of a synthetic antiferromagnet. In the case of the first method, in order to build up the digitizing grid, we realized in a first phase a cylindrical body with an elliptic basis, and then we built up the sample digitization grid; in the last stage we selected two zones and we associated them with the two ferromagnetic layers.

In the second method used to build up the digitization grid for a SAF structure, two cylinders with elliptical basis were formed at first, then they were interconnected, forming a cylinder with the same basis, but with its height equal to the sum of the heights of the two constituent cylinders, and finally the digitizing network is generating.

This last method offers a symmetric major hysteresis loop and the two ferromagnetic layers are very well bounded, which gives us the possibility to view exactly the distribution of the magnetic moments from each ferromagnetic layer.

The subchapter "*Study concerning the critical curves for the SAF structures in the approximation of micromagnetic model*" comes with a comparative model to the SAF model in the microspins approximation presented in chapter 2. In order to analyze the size effect on the critical curves that characterize a SAF structure, we used a micromagnetic model based on the finite element method.

The SAF structures were digitized with a grid element equal to 2 nm, such that finally, an approximate number of 55000 nods and 10000 elements for the sample with the biggest size results. In order to perform a study concerning the dynamics of the magnetization of the two ferromagnetic layers from the SAF structure, the Landau- Lifshitz- Gilbert equation is used, solved for each nod.

The details related to the pulse shape, the characteristics of pulse construction, and details concerning the geometry of the three utilized samples are discussed again in the SAF model for two macrospins.

We can draw the conclusion that both, the external and the internal critical curves diminish their aria within the space of magnetic field components application with the increase of the elliptic basis of the SAF structures. Unlike the switching diagrams obtained in the SAF model for two macrospins, one can notice that the switching diagrams occupy larger values of the applied fields region (H_puls, H_bias), since the micromagnetic model takes also into account the exchange interactions between neighboring finite elements. Still another aspect from critical curves evolution is given by the fact that in the case of micromagnetic model there are no overlapping of the external critical curves due to the way in which the demagnetizing magnetic field is computed (using scalar potentials from interior and the margins for each digitizing element)[1].

The last sub-chapter presents a mechanism to show off the commutation process in the SAF structure through the representation of the projections of ferromagnetic layer magnetization in the easy direction of magnetization.

The *General Conclusions* derived from the chapters 2 and 3 are presented at the end of the dissertation manuscript:

- For micromagnetic simulations on both amorphous nanowires and synthetic antiferromagnet structures, based on the finite elements method, we used the Magpar programs package. We installed this program package on the university cluster, which gives us the possibility to run problems requiring a number of 520 processors and about 1 TB RAM memory. As the Magpar is built on parallel calculation algorithms, we configured the cluster such that to have a common storage space for all the servers. After installing Magpar, we implemented the test problems denounced by the μMag group, in order to verify the accuracy of the obtained results. Studies were performed concerning the computing program performances (processor consumption, memory, implementation and execution time, utilized network resources) in order to determine the optimum simulation conditions for various micromagnetic problems.
- The micromagnetic simulations that use the finite element method require the sample digitization in finite elements. For the study of amorphous wires switching, we chose cylinders with the diameters of 4 μm and lengths from 10 to 150 μm. These cylinders were digitized with a finite parameter of digitization (maximum distance between two neighboring nods) of 200 μm, which results in problems with dimensions of 130,000 to 2.000.000 elements. In the case of magnetization switching in SAF structures, the SAF samples were digitized with a grid element equal to 2 nm, such that it comes to about 55000 nods and 10000 elements for the sample with the biggest dimensions. We used two methods for the digitization of the SAF structures.
- In the case of the study on amorphous wires, we presented a systematic micromagnetic investigation concerning the role of the mechanic stress in the magnetization processes of the micrometric amorphous wires. Starting from stress distribution based on the calculus from specialized literature and using realistic material parameters, we obtained results agreeing with the observed domain structure and magnetization curves for:
    - Wires with positive magnetostriction, which show a core-coating domain structure, with a “maze-like” surface domain structure (the moments being oriented radially) and an axial magnetized domain, correlated with the magnetic behavior noticed until now, and characterized by a big jump of the magnetic moments at the coercive force.
    - Wires with negative magnetostriction have an almost non-hysteretic magnetization curve which, through switching based on reversible rotations, form circumferential domains across the entire wire section.
- Magpar in its original form allows the study of magnetostatic interactions between sample separated regions and exchange interactions between the regions connected to the digitizing network. Starting from the study of the

manner in which the exchange interaction was introduced in the program package, we used the interaction of the antiferromagnetic coupling between the two ferromagnetic layers. In order to carry out studies on the switching of a synthetic antiferromagnet structure using both the macrospin models and micromagnetic models, we introduced in the programs a succession of perpendicular magnetic fields whose increases and decreases were realized using a sine function.

- In order to determine the size effect on the switching diagrams of critical curves in SAF structures, we performed a comparative study between a SAF model whose ferromagnetic layers are approximated by two macrospins, and a micromagnetic model, whose samples have been digitized in finite elements. In the both models we considered SAF cylindrical structures with elliptic basis, made of two ferromagnetic *Permalloy* layers, with the heights of 5 nm and 7 nm respectively. The basis of the first sample was an ellipse with the major axis of 24 nm (in the Ox direction) and the minor axis of 20 nm (in the Oy direction). The elliptic bases of the two samples used in simulation were two and three times bigger than the basis of the first sample. We can draw the conclusion that both the external and the internal critical curves diminish their area within the space of application of the magnetic field components, with the increase of the elliptical basis of the SAF structure. Unlike the switching diagrams obtained in the SAF model for two macrospins, one can notice that the switching diagrams occupy higher values of the applied field region (H_puls, H_bias), because the micromagnetic model takes also into account the spin interactions between neighboring finite elements. Still another aspect in the evolution of the critical curves is given by the fact that in the case of the micromagnetic model there are no overlapping's of the external critical curves, given the way in which the demagnetizing magnetic field is calculated (by using the scalar potential from inside and the margins from each digitizing finite element).

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During the doctoral studies, I participated in **21 national/international conferences with: 8 viva voce presentations and 13 poster presentations**; I was member of **3 grants**, attended the courses of the **summer school from the USA** and I participated in the organization of **3 conferences.**

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